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(54) SENSING OF FORCE AND TORQUE COMPONENTS TRANSMITTED BETWEEN MEMBERS

(71) We, STANFORD RESEARCH, INSTITUTE, a corporation organised and existing under the laws of the State of California, United States of America, of Menlo Park, California 94025, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to sensing force and torque components transmitted between first and second members and is particularly, but not exclusively, concerned with manipulators.

Position controlled manipulators for industrial and scientific use are well known and often are used in automatic operations of manufacture, assembly, etc. Control systems for the automatic control and/or operation of manipulators may be of the open loop or closed loop type. Closed loop systems generally necessitate the use of a computer, such as a digital computer, to handle the necessary coordinate conversions, control equations and completion criteria. To carry out an assigned manipulative task requires the sensing of torques and forces at various manipulator locations. Forces or torques at the joints of the manipulator may be sensed by measuring the current supplied to driving motors or the back pressure in hydraulic systems used to operate the joints. Such joint force measurements are of limited usefulness, however, for a number of reasons including contamination by both the weight of the manipulator segments and the weight of the load and the presence of friction in the back drivability of individual joints. For example, depending on the gearing employed, more than 10 percent of the force exerted by a joint may be required to back drive the same. The use of joint forces, therefore, is best suited to the detection of collisions of the manipulator with obstacles encountered during a task.

Another means of measuring contact be-

tween the manipulator end effector (such as manipulator hand) and the environment is to measure the force couple at some point on the manipulator, preferably as close to the end effector as possible. The force couple consists of a torque vector and a force vector describing the reaction at said point. By sensing of the force couple at the wrist, gravitational and acceleration loading on the manipulator components behind the wrist have no effect on the sensing mechanism, and only gravity and acceleration loading from the combined mass of the end effector (e.g., hand) and object gripped determine the force couple at the wrist. A computer controlled arm employing wrist sensing means is shown, for example, in the article entitled "Force Feedback Steering of a Tele-operator System" by R. C. Groome, Jr., MIT Charles Stark Draper Lab. Report T-575, Cambridge, Mass., August 1972. The present invention is particularly, but not exclusively, directed to a greatly simplified wrist sensing means capable of operation over a wide load range.

According to a first aspect of the invention, there is provided sensing means for use in sensing at least one component of force along and torque components about mutually orthogonal X, Y and Z axes, said components being transmitted between first and second members having a longitudinal axis extending along the Z axis, the sensing means comprising: resilient coupling means coupling said first and second members to allow for relative movement therebetween and through which said X, Y and Z axes extend; a plurality of sensing units displaced from the Z axis at the resilient coupling means, each of which sensing units includes first and second cooperating means attached to the coupled first and second members, respectively, so that relative movement between the first and second cooperating means is produced upon transmission of forces and torques between the coupled first and second members

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through the resilient coupling means, the torques and forces being transmitted through the resilient coupling means substantially independently of the sensing units; and means for obtaining at least first and second electrical outputs from each of the sensing units, the outputs from each sensing unit being respectively responsive only to relative movement of the cooperating means along a first direction parallel to the Z axis and perpendicular to a radius extending from the Z axis through the associated sensing unit, and only to relative movement of the cooperating means along a direction orthogonal to the associated first direction and radius.

According to a second aspect of the invention, there is provided sensing means for use in sensing components of force along and components of torque about mutually orthogonal X, Y and Z axes extending through resilient coupling means coupling first and second members together, the Z axis extending longitudinally therethrough, the sensing means comprising: at least three sensing units spaced about the resilient coupling means on the circumference of a circle concentric with the Z axis; each of the sensing units including first and second cooperating means attached to the coupled first and second members, respectively, so that relative movement between the first and second cooperating means is produced upon transmission of forces and torques through the resilient coupling means; means for obtaining first electrical outputs from each of the sensing units responsive only to relative movement of the cooperating means along a direction parallel to the Z axis; means for combining said first electrical outputs for obtaining outputs indicative of torque components about the X and Y axes and a force component along the Z axis; means for obtaining second electrical outputs from each of said sensing units responsive only to relative movement of the cooperating means along a direction mutually orthogonal to a radius extending from the Z axis through the sensing unit and a direction parallel to the Z axis; and means for combining said second electrical outputs for obtaining outputs indicative of force components along the X and Y axes and a torque component about the Z axis.

According to a third aspect of the invention, there is provided a method of sensing components of force along and components of torque about mutually orthogonal X, Y and Z axes, said components being transmitted between first and second members, the method comprising: attaching the first and second members together by resilient coupling means through which substantially the entire force and torque components are transmitted between the first and second members; attaching a plurality of two-part sensing units, at locations spaced about the circumference of a

circle concentric with the Z axis and in the plane of the X and Y axes, to the first and second members such that relative movement between the two parts of the sensing units is produced upon transmission of forces and torques through the resilient coupling means; obtaining first electrical outputs from the sensing units in response to relative movement of the two parts along a direction parallel to the Z axis; combining the first electrical outputs in respective different manners to obtain outputs respectively related to torque components about the X and Y axes and a force component transmitted along the Z axis; obtaining second electrical outputs from the sensing units in response to relative movement of the two parts of each sensing unit along a direction orthogonal to a radius of the Z axis passing through the associated sensing unit and the direction parallel to the Z axis; and combining the second electrical outputs from the sensing units in respective different manners to obtain outputs respectively related to force components transmitted along the X and Y axes and a torque component about the Z axis.

Sensing means embodying the invention are particularly suited for use in manipulators. Hereinbelow there is described a manipulator which includes an effector, such as a hand, comprising a pair of jaws relatively pivotally movable between open and closed positions under operation of power means such as an electric motor. Sensing means embodying the invention, for sensing both magnitude and direction of forces along the three mutually orthogonal axes intersecting at the wrist and for sensing magnitude and direction of torques about said axes, are provided at the wrist intermediate to the manipulator hand and hand supporting means. The sensing means includes the plurality of sensing units which are spaced from the longitudinal axis of the manipulator at equal distances therefrom. Four such orthogonally located sensing units are employed, each of which includes a radially extending opaque pin carried by the manipulator arm or hand. Each pin extends into a clearance hole formed in a housing carried by the other of the arm and hand. Each housing is formed with passages which intersect the pin receiving hole and along which passages an associated energy (e.g. light) source and energy detector are located, with the energy from the source being directed toward the energy detector. A portion of the energy from each of the sources is blocked by the pin such that only the unobstructed portion of the energy from the source reaches the detector. The amount of shadowing of energy by the pins depends upon forces and torques applied to the hand, and the outputs from the detectors are combined in such a manner as to provide output signals representative of the three components

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of force at the wrist corresponding to reach, lift and sweep directions of hand motion and the three components of torque corresponding to twist, the measurement of each said component being substantially independent of the measurement of each of the others. Also, the hand and power means for operation of the wrist, such that the power means functions as a counterweight to balance the weight of the hand. Consequently, the hand weight is not reflected in the outputs of the torque sensors.

The invention will now be further described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a plan view of a manipulator including wrist sensing means embodying this invention, showing portions of the wrist sensing means and a jaw actuating mechanism broken away for clarity;

Figure 2 is a view taken substantially along line 2—2 of Figure 1;

Figure 3 is a fragmentary exploded view of the manipulator and including an identification of the wrist axes and the forces along and torques about such axes to which the wrist sensing means is responsive;

Figure 4 is a sectional view taken along line 4—4 of Figure 1;

Figure 5 is a sectional view taken substantially along line 5—5 of Figure 4 showing one of a plurality of sensing units constituting the wrist sensing means;

Figure 6 is an enlarged perspective view of one of the sensing unit housings;

Figure 7 is a schematic circuit diagram showing a pair of photocells connected together in a difference circuit arrangement;

Figure 8 is a longitudinal sectional view of a coupling means showing a modified form of sensing unit employing potentiometers;

Figure 9 is a sectional view taken along line 9—9 of Figure 8 showing resistance elements of the potentiometers;

Figure 10 is a circuit diagram showing outputs from a pair of potentiometers supplied to two difference circuits having outputs indicative of force along and torque about different axes;

Figure 11 is a longitudinal sectional view of a coupling means showing a further modified form of sensing unit employing split photocell elements; and

Figure 12 is a sectional view taken along line 12—12 of Figure 11 showing the photocell faces.

Reference now is made to Figures 1, 2 and 3 of the drawings wherein a manipulator is shown comprising a hand supporting member 10 capable of being coupled by threads 12 to a robot, automated machinery, earth, space or underwater vehicle, or the like (not shown) such as are presently in use. The member 10 is coupled through a wrist sensing means

embodying this invention, identified generally by the reference numeral 14, to a gear box or housing 16 included in the manipulator hand. A detailed description of the wrist sensing means is contained hereinbelow.

For present purposes, it will be understood that the wrist sensing means 14 includes a ring 18, one side of which is secured to a base 22 of the housing 16 as by screws 24 extending through holes in the base into threaded holes in the ring to secure the base and ring together. A reversible motor 20 is secured to this assemblage by means of screws 23 extending through threaded holes in a flange 22' on the base 22 of the housing 16 into holes in the motor base. Resilient coupling means 26, such as pads of rubber or like resilient material, are cemented or otherwise suitably secured between the forward face 27 of the member 10 and rearward face 28 of the ring 18 to secure the ring 18 (with the attached gear housing 16 and motor 20) to the member 10. The resilient coupling means 26 are deformed upon transmission of forces therethrough, and orthogonally positioned sensing units 25-1, 25-2, 25-3 and 25-4 located adjacent the coupling means provide a measure of the force and torque at the intersection of the X, Y and Z axes identified in Figure 3.

The reversible motor 20 serves to open and close a pair of jaws 29 and 30 through a suitable gear and linkage mechanism which now will be described. The motor shaft 32 extends through the ring 18 and an aperture in the base plate 22 and into the housing 16. A pinion 34 at the forward end of the motor shaft engages a pair of inwardly facing bevel gears 36 and 38 which are independently rotatably supported on a shaft 40 extending between the upper and lower walls 42 and 44, respectively, of the housing 16, as seen in Figure 2. The upper wall 42, which is removable to facilitate assembly, is shown broken away for clarity in Figure 1. Attached to or formed on the bevel gears 36 and 38 at the outer sides thereof are spur gears 46 and 48 which engage sector gears 50 and 52, respectively, for drive actuation thereof. The sector gears 50 and 52 are rotatably mounted on shafts 54 and 56, respectively, extending between the upper and lower walls of the housing 16.

A first pair of parallel links 58 and 60 connect the one jaw 29 to the gear housing 16, and a similar second pair of parallel links 62 and 64 connect the other jaw 30 to the housing. At the housing the links 58 and 62 are pivotally supported on the shafts 54 and 56 about which the sector gears pivot. The links 60 and 64 are pivotally mounted on shafts 66 and 68 between the housing walls 42 and 44. Pins 70 connect the forward ends of the links 58, 60, 62 and 64 to the jaws 29 and 30. The inner links 58 and 62 are

slotted to receive the sector gears 50 and 52, respectively, and screws 72 secure the links to the gears.

Operation of the jaws 29 and 30 between open and closed position, although believed to be apparent, will now be briefly described. When the motor 20 is energized for rotation of the bevel gear 34, the meshing bevel gears 36 and 38 are counterrotated. The counterrotating gears 36 and 38 drive the gear segments 50 and 52 in counterrotating directions through the spur gears 46 and 48. The links 58 and 62 attached to the gear segments are thereby counterpivoted for closing or opening of the jaws. The links 60 and 64, which are parallel to the driven links 58 and 62, respectively, maintain the jaw faces in parallel relation.

The jaws 29 and 30 may be of a generally hollow construction to accommodate force sensors having actuating means at the jaw faces. As seen in Figures 1 and 2, the inner facing walls of the jaws may be provided with 18 force transducers actuated by a 3×6 array of actuating members such as buttons 76. Other force transducers are included which are under control of actuating plates 78-1 through 78-7 at other jaw surfaces. Also, mounted within the jaws and extending from the inner jaw faces are slip sensors 80 which are orthogonally positioned for sensing object slip transversely and longitudinally of the jaw faces. The force transducers and slip sensors are disclosed in our copending U.K. Patent Application No. 636/75, (Serial No. 1,370,351), to which reference should be made.

The wrist sensing means 14, as mentioned above, includes the four sensing units 25-1, 25-2, 25-3 and 25-4 located along the X-Y axes thereof. The Z axis of the three mutually orthogonal axes extends along the longitudinal center of the manipulator. The sensing means functions to sense the direction and magnitude of forces acting along the three axes and the direction and magnitude of the force moments thereabout. Where the sensing means are employed in a manipulator, as shown in Figures 1-7 of the drawings, the forces along the X, Y and Z axes comprise sweep, lift and reach forces, respectively, and the force moments thereabout comprise tilt, turn and twist torques, respectively. In Figure 3, arrows indicating positive direction of torque about the X, Y and Z axes are identified as M_x , M_y and M_z , respectively.

As best seen in Figures 1, 3 and 4, the member 10 comprises a cylindrically shaped housing having at the forward end thereof forwardly extending quadrature spaced arm members 82. Threaded holes are formed through the arms 82 for the support of radially extending opaque pins 84 having enlarged threaded heads in threaded engagement with the threaded holes. The pins, as

will become apparent hereinbelow, function to block varying amounts of light along light paths extending generally tangentially to the pins, with the amount of light passing thereby being dependent upon the forces and torques at the sensor. The ring 18 similarly is provided with rearwardly extending quadrature spaced arm members 86 radially spaced from the arms 82. In the illustrated arrangement, the arms 86 are inwardly radially spaced from the arms 82 and support housing members 88, which are attached thereto by screw fasteners 90 extending through symmetrically located holes in the arms and engaging threaded holes 92 (see Figure 6) in the housing members. The arms 86 and attached housings 88 are formed with colinear clearance holes 94 and 96, respectively, into which the opaque pins 84 coaxially extend. The pins are spaced from the hole walls to allow for displacement of the normally coaxially extending pin and hole axes in operation.

For simplicity of manufacture all of the housing members 88 may be of identical construction comprising, in addition to the mounting holes 92 and pin receiving hole 96, light passages 98 extending there-through. The light passages 98 intersect the pin receiving aperture 96, with the axes thereof extending substantially tangentially of the pin 84 when the pin and aperture 96 are coaxially located. In the illustrated arrangement there are four parallel extending light passages which terminate at one pair of opposite faces of the generally cubical housing 88 and two parallel extending light passages which terminate in another pair of opposite housing faces, with none of the light passages intersecting any other light passage. In attaching the housings 88 to the arms 86, one housing 88 (at sensing unit 25-1) is arranged with the four light passages 98 extending parallel with the longitudinal Z axis, and the other three housings 88 (at sensing units 25-2, 25-3 and 25-4) are arranged with the two parallel light passages extending parallel with the Z axis.

Not all of the light passages are utilized in the sensing operation but, as mentioned above, are formed in the housings 88 for uniformity and simplicity of construction. Certain passageways are provided with light source and light sensing means identified generally by reference numerals 100 and 102, respectively, at opposite ends of the passageways. The light source and sensing means may comprise, for example, light emitting diodes and photo-transistors, respectively, although it will be apparent that the invention is not limited to the use of such means. To differentiate between the various light source and sensing means in the description and drawings, the reference numerals 100 and 102 are followed by abbreviations for

identification of the force or torque sensed thereby together with a plus or minus sign for indicating direction thereof. For example, reference characters 102X⁺ and 102X⁻ identify the two sensing means used in the measurement of forces along the X axis. Similarly the reference characters 102M_x⁺ and 102M_x⁻ identify those sensing means used in the measurement of the moments of force (i.e., torque) about the X axis. The light source and sensing means employed in the force and torque measurements about the Y and Z axes are similarly identified.

As noted above, the axes of the light passages extend substantially tangentially to the opaque pins 84 in the neutral, central position of the pins within the clearance holes 96. In this position, as seen in Figures 4 and 5, the pins shield approximately half the light from each source 100, preventing the shielded portion from reaching the associated photocell at the opposite end of the passageway. That is, the shadow of the pin covers approximately one half the active face of the associated photocell, with the pin centrally axially located in the clearance hole. Movement of the opaque pin within the clearance hole toward or away from the light beam increases or decreases the shielding effect by the pin to decrease and increase, respectively, the amount of light reaching the associated photocell. Where the photocells comprise phototransistors, the output therefrom increases with an increase in light received.

It will here be noted that any change in the amount of light from a light source passing a pin 84 is dependent upon that component of relative movement of the pin axis toward or away from the light beam axis and is substantially independent of movement in any other direction. Referring to Figure 5, for example, it will be apparent that movement of the pin 84 to the left along the X axis will block more light from the source 100M_x⁺, thereby casting a larger shadow in the photocell 102M_x⁺ to decrease the photocell output. Movement of the pin along the Z axis merely moves the pin along the light beam axis between the source 100M_x⁺ and sensor 102M_x⁺ without producing a significant change in the amount of light passing the pin. Similarly, movement of the pin along the Y axis, into or out of the plane of the drawing figure, has no effect on the light passage between said source 100M_x⁺ and sensor 102M_x⁺. It will further be noted that relative movement between the opaque pin and light beam axes toward or away from each other may be effected by either relative translational movement along one manipulator axis or by relative rotational movement about the center of the sensor in the plane extending transversely to the light beam axis, whereby both force and torque vector sensing

about the X, Y and Z axes is possible, as will now be described.

The translational and rotational movements about the three orthogonal manipulator axes are independently sensed by use of pairs of properly located light sensors at diametrically opposite sensor units. Reference is made to Figure 3 wherein the sensors 102X⁺ and 102X⁻ at the diagonally opposite units 25-3 and 25-1, respectively, along the Y axis are shown for sensing light along light beam axes extending parallel with the Z axis. The sensors are located at opposite sides of the Y-Z plane, that is, the plane determined by the intersecting Y-Z axes. In the drawings the sensors 102X⁺ and 102X⁻ are shown located to the side of the Y-Z plane in the positive and negative X axis directions, respectively. With no X direction (i.e., sweep) force on the manipulator, the outputs from the photocells 102X⁺ and 102X⁻ are equal. A sweep force, however, will produce a differential change in the photocell outputs. For example, a force in the positive X direction will result in translational movement along the X axis of the pins 84 within the housings 88, whereupon the light reaching the photocell 102X⁺ increases whereas the light reaching the photocell 102X⁻ decreases. Conversely, a sweep force in the opposite direction will result in a lower output from the photocell 102X⁺ and a higher output from the photocell 102X⁻.

The outputs from the pair of photocells 102X⁺ and 102X⁻ are connected to or included in a differential circuit having no output when the photocell outputs are equal and having an output of one or the other polarity dependent upon which photocell output is the largest. Where the photocells 102X⁺ and 102X⁻ comprise phototransistors, a simple circuit such as that shown in Figure 7 may be employed. There, the phototransistor emitter and collector electrodes are shown connected in series circuit between positive and negative 15 volt supplies. With equal light impingement on the phototransistors, equal currents flow therethrough, whereby the potential at the output terminal 106 is zero. If more light strikes one phototransistor than the other, a positive or negative output voltage is produced, depending upon which phototransistor is most conductive, the magnitude of which output depends upon the light difference at the phototransistors.

It will be seen that lift and reach forces on the manipulator produce no change in the sweep sensing photocell 102X⁺ and 102X⁻ outputs since, as noted above, such forces result in relative movement of the opaque pins and associated light beam axes having no component in the X direction to change the distance between the light beam axes and pins. Similarly, it will be seen that tilt and turn torques produce no substantial changes in the photocell 102X⁺ and 102X⁻ outputs.

A twist force moment (i.e., torque about the Z axis) will change the photocell 102X⁺ and 102X⁻ outputs. Note, however, that since the photocells 102X⁺ and 102X⁻ are located at opposite sides of the Y—Z plane, the photocell outputs change in the same direction the same amount. For example, with a positive twist more light is received by both photocells 102X⁺ and 102X⁻, whereby the outputs therefrom increase. However, since the photocells are connected in an electrical difference circuit arrangement, as shown in Figure 7, there is no resultant output change at the output terminal 106 with equal changes in current flow through the phototransistors. Consequently, sweep force sensing by the photocells 102X⁺ and 102X⁻ also is substantially immune to torque about the Z axis.

The left sensing photocells 102Y⁺ and 102Y⁻ at sensing units 25-2 and 25-4 are electrically connected together in a difference circuit, such as the circuit for the sweep sensing photocells shown in Figure 7, the output of which circuit provides an indication of the direction and magnitude of the lift force along the Y axis. The photocell arrangement is similar to that of the sweep sensing photocells at the orthogonally located sensing units 25-1 and 25-4 and requires no additional description.

The reach sensing photocells 102Z⁺ and 102Z⁻ for force sensing along the Z axis may be located at either diagonally opposite sensing units 25-1 and 25-3 or units 25-2 and 25-4 and, as shown in Figure 3, are located at the units 25-1 and 25-3. The parallel light beam axes for the photocells 102Z⁺ and 102Z⁻ extend parallel to the X—Y plane at opposite sides thereof. With a positive reach force, it will be seen that the pins 84 move rearwardly with respect to the housings 88, whereby the photocell 102Z⁺ at the forward side of the X—Y plane receives more light and the photocell 102Z⁻ to the rear of the X—Y plane receives less light. Again, the photocell outputs are connected in a difference circuit (such as shown in Figure 7) having an output magnitude related to the reach force and polarity related to the direction thereof. Also, forces along other axes and torques about the X—Y and X axes either have no effect on the photocell outputs or else produce the same change in both photocell outputs, which changes cancel out in the output from the difference circuit in which the photocell outputs are included.

Torque sensing about the X, Y and Z axes for measurement of the magnitude and direction of tilt, turn and twist, respectively, now will be described. The tilt sensing photocells 102M_x⁺ and 102M_x⁻ are located at the diametrically opposite sensing units 25-1 and 25-3, with the light beam axes associated therewith extending parallel with the X axis. Both photocells are located at the same side

of the X—Y plane and, for purposes of illustration, are shown forwardly thereof in the negative Z direction. It will be apparent, then, that upon application of a tilt torque, light at one photocell is increased while that at the other is decreased. The photocell outputs are included in a difference circuit, such as that shown in Figure 7, the output from which circuit has a magnitude dependent upon the amount of tilt torque and a polarity dependent upon the direction thereof. The only other movement which produces a change in the photocell 102M_x⁺ and 102M_x⁻ outputs is produced by a reach force. It will be noted that positive and negative reach forces result in increased and decreased outputs, respectively, from both photocells, which cancel in the output from the difference circuit.

Torque about the Y axis is measured by use of the photocells 102M_y⁺ and 102M_y⁻ having outputs connected in a difference circuit arrangement, which photocell and circuit arrangement are similar to those of the X axis torque measurement means described above and need not be described in any further detail.

It will be readily apparent that twist may be measured by photocells located at either pair of diagonally opposite sensing units. In the drawings the photocells 102M_z⁺ and 102M_z⁻ for twist measurement are located at the sensing units 25-1 and 25-3 at the ends of light passages which extend parallel with the Z axis and which are located at one side of the Z—Y plane. As will all of the other pairs of photocells, the photocell outputs are connected in a difference circuit, an exemplary circuit arrangement being shown in Figure 7.

Sweep and lift forces which result in translational movement of the pins relative to their associated sensor housings load the coupling means 26 in shear. The amount of movement for any given force will, of course, depend upon the shear stress-strain characteristics of the coupling means. A reach force subjects the coupling means to either a tensile or compressive stress, depending upon direction, and the amount of movement depends upon the tensile and compressive stress-strain characteristics. Torque loading about any axis subjects the coupling means to a combination of tensile and compressive forces. Since the tensile and compressive stress-strain characteristics of a material generally are quite different, it will be apparent that a torque about an axis will result both in a rotational movement and a small translational movement. The accompanying translational movement, however, is not sufficient to grossly adversely effect the outputs from the photocells, including other photocells not utilized in the particular torque measurement, and may be compensated for in the equipment using the sensor.

The coupling means 26 may be selected for the desired properties and stress-strain characteristics for operation of the manipulator within any desired range of force couples. Elastomeric material, such as natural or synthetic rubber, plastics or the like, may be used for the coupling means 26. Other suitable coupling means include resilient beams, coil or leaf springs, or the like, having suitable properties in shear, compression and tension for the intended application. To further alter or extend the operating range, composite coupling means 26 made, for example, of sections or layers of different material may be employed.

The sensing method and means are not limited to use with the light beam sensors described above. Other sensing units, including other photocell-type sensors and potentiometer-type sensors, may be used at a radially spaced distance from the resilient coupling for sensing the two perpendicular components of movement mutually perpendicular to the radius therethrough independently of radial motion thereat. Reference is made to Figure 8 wherein a supporting member 10' is shown connected through resilient coupling means 26 to a supported member 18'. Force and torque sensing units 110-1, 110-3 and 110-4 (together with a fourth sensing unit, not shown) are orthogonally located a radial spaced distance from the longitudinal Z axis of the resiliently coupled members 10' and 18' in a transverse plane extending through said coupling means 26. Here, the sensing units each include two potentiometer-type sensors designated 112-1 and 112-2, one for sensing movement parallel to the Z axis and the other for sensing movement in a direction mutually orthogonal thereto and to the radius therethrough.

Each sensor includes a first element comprising a rectangular shaped plate of resistive material 114 and a second element comprising contact 116 relatively movable over the surface of the resistive plate in substantially point contact therewith. The resistive elements 114 are attached to spaced longitudinally extending arms 82' on the supporting member 10' through insulating blocks 118, and the cooperating contacts 116 are carried in blocks 120 of insulating material attached to the supported member 18'. The contacts, which are radially movable within the apertures in the mounting blocks 120, are resiliently biased radially outwardly by springs 122 at the base of the apertures, and output leads 124 are attached to the contacts through said springs.

As also seen in Figure 9, electrodes 126 are provided along a pair of opposite edges of the resistive elements 114, which electrodes are connected to equal magnitude but opposite polarity potentials V+ and V-. As viewed in Figure 9, the electrodes 126 for the sensor

112-2 which are parallel to the Z axis are at right angles to the electrodes for the sensor 112-1 which are parallel to the X axis. With the contacts 116 at the center of the resistive elements, no output voltage is obtained therefrom. Movement from the center toward the V+ electrode will result in a positive output, and a conversely, movement from the center toward the V- electrode will result in a negative output. It will be seen, then, that each sensor is responsive to relative movement along one axis and is insensitive to movement along the other axes. The pair of sensors 112-1 and 112-2 at any given sensing unit thereby provide outputs indicative of movement from the neutral position along two orthogonal axes mutually orthogonal to a third axis extending radially through the sensing units.

Outputs from sensors at diametrically opposite sensing units are connected to suitable difference circuitry to obtain the desired force and torque output signals. In Figure 10, to which reference now is made, the outputs from sensors 112-1 at diametrically opposite sensing units 110-1 and 110-3 are shown connected directly to one differential amplifier 130 and are shown connected through an inverter amplifier 132 to another differential amplifier 134. The outputs from the amplifiers 130 and 134 are, therefore, proportional to torque about the X axis and force along the Z axis, respectively. Other pairs of sensor outputs are similarly connected together in arrangements which will be obvious, in view of the above description, to obtain other force and torque components, as desired.

A force and torque sensing means employing sensing units of another modified form is shown in Figures 11 and 12, to which figures reference now is made. As with the arrangement of Figure 8, the supporting and supported members 10' and 18' are coupled together through resilient coupling means 26 to allow for relative movement therebetween upon transmission of forces or torques there-through. Again, three of the four quadrature spaced sensing units designated 140-1, 140-3 and 140-4 are shown. Each sensing unit includes a pair of light sources 142, such as light emitting diodes, attached to one of the members 10' and 18' for production of radially directed light beams. In the illustrated arrangement, the sources are carried in blocks 144 attached to the member 18' and are positioned to direct light beams radially outwardly through masks 146 having square apertures 148 formed therein. The square cross sectional shaped beams from the apertures impinge upon split photocells 150 having two adjacent light responsive elements at the face thereof. Outputs from the two photocell elements are obtained from output leads designated O₁ and O₂. At adjacent photo-

cells 150 of a sensing unit, the lines designated 152 between adjacent photocell elements are perpendicular, as seen in Figure 12, whereby movement in two orthogonal directions mutually orthogonal to the line extending radially through the sensing unit is detected. Photocell outputs from diametrically opposite sensors are connected together in difference circuits in the manner described above for the Figures 1—7 arrangement to obtain signals representative of the force and torque components transmitted by the coupling means 26. It will here be noted that outputs from commercial four-quadrant photocells can be combined in sum and difference amplifiers to obtain the same outputs obtained from pairs of two half photocells shown.

The invention can be embodied in other ways than those described above by way of example. For example, to prevent ambient light errors the wrist sensing means employing photocells may be enclosed in an opaque covering or housing (not shown). Also, devices with only one pair of sensing units, such as units 25-1 and 25-3 or units 25-2 and 25-4, may be employed without the other pair for force and torque sensing of a limited nature. Three sensing units spaced around the wrist (as 120 degree equal spacing) also can be used to sense all three forces and three torques. Here, either by proper placement of photoemitting and photosensitive cells using difference circuits as in Figure 7 or by using only three pairs of light beams and differential amplifiers to combine the outputs, all three forces and three torques can be separately obtained.

WHAT WE CLAIM IS:—

1. Sensing means for use in sensing at least one component of force along and torque components about mutually orthogonal X, Y and Z axes, said components being transmitted between first and second members having a longitudinal axis extending along the Z axis, the sensing means comprising:

resilient coupling means coupling said first and second members to allow for relative movement therebetween and through which said X, Y and Z axes extend;

a plurality of sensing units displaced from the Z axis at the resilient coupling means, each of which sensing units includes first and second cooperating means attached to the coupled first and second members, respectively, so that relative movement between the first and second cooperating means is produced upon transmission of forces and torques between the coupled first and second members through the resilient coupling means, the torques and forces being transmitted through the resilient coupling means substantially independently of the sensing units; and

means for obtaining at least first and second

electrical outputs from each of the sensing units, the outputs from each sensing unit being respectively responsive only to relative movement of the cooperating means along a first direction parallel to the Z axis and perpendicular to a radius extending from the Z axis through the associated sensing unit, and only to relative movement of the cooperating means also a direction orthogonal to the associated first direction and radius.

2. Sensing means according to claim 1, wherein said plurality of sensing units are spaced about the circumference of a circle concentric with said longitudinal axis at the resilient coupling means, and including means for connecting electrical outputs from different sensing units together in circuit arrangements having outputs algebraically related to the electrical outputs from the sensing units.

3. Sensing means according to claim 1, wherein first and second said sensing units are located along the Y axis on opposite sides of the Z axis, and wherein the first and second electrical outputs from each of the sensing units are responsive only to relative movement of the cooperating means along directions parallel to the X and Z axes, respectively.

4. Sensing means according to claim 3, including means for connecting electrical outputs from the first and second sensing units together in circuit arrangements having outputs algebraically related thereto, one of the circuit arrangements having an output indicative of force transmitted along the X axis and another of the circuit arrangements having an output indicative of torque about the X axis.

5. Sensing means according to claim 4, wherein a further said circuit arrangement has an output indicative of torque about the Z axis.

6. Sensing means according to claim 4 or claim 5, wherein a further said circuit arrangement has an output indicative of force transmitted along the Z axis.

7. Sensing means according to any one of claims 3 to 6, wherein third and fourth said sensing units are located along said X axis on opposite sides of the Z axis, the first and second electrical outputs from each of the third and fourth sensing units being responsive only to relative movement of the cooperating means along directions parallel to the Y and Z axes, respectively, and including means for connecting the electrical outputs from the third and fourth sensing units together in circuit arrangements having outputs indicative of force transmitted along and torque transmitted about the Y axis.

8. Sensing means for use in sensing components of force along and components of torque about mutually orthogonal X, Y and Z axes extending through resilient coupling means coupling together first and second

members which have a longitudinal axis extending along the Z axis, the sensing means comprising:

5 at least three sensing units spaced about the resilient coupling means on the circumference of a circle concentric with the Z axes;

10 each of the sensing units including first and second cooperating means attached to the coupled first and second members, respectively, so that relative movement between the first and second cooperating means is produced upon transmission of forces and torques through the resilient coupling means;

15 means for obtaining first electrical outputs from each of the sensing units responsive only to relative movement of the cooperating means along a direction parallel to the Z axis;

20 means for combining said first electrical outputs for obtaining outputs indicative of torque components about the X and Y axes and a force component along the Z axis;

25 means for obtaining second electrical outputs from each of said sensing units responsive only to relative movement of the cooperating means along a direction mutually orthogonal to a radius extending from the Z axis through the sensing unit and a direction parallel to the Z axis; and

30 means for combining said second electrical outputs for obtaining outputs indicative of force components along the X and Y axes and a torque component about the Z axis.

35 9. Sensing means according to claim 8, wherein there are four of said sensing units spaced around the circumference of said circle and located along the X and Y axes.

40 10. Sensing means according to any one of claims 1 to 9, wherein the first and second cooperating means of at least one of the sensing units include an opaque member and spaced apart light source and light sensing means, respectively, arranged so that light from the source is directed toward the light sensing means past an edge of the opaque member, which opaque member blocks a variable portion of the light preventing the same from reaching the photocell.

50 11. Sensing means according to claim 10, wherein the opaque member extends into a clearance hole in a housing, the light source and light sensing means being at a light passage defined in the housing and intersecting the clearance hole.

55 12. Sensing means according to claim 11, including a plurality of said light passages formed in the housing means and intersecting the clearance hole, the light passages extending along substantially perpendicular axes, and a light source and light sensing means at opposite ends of each said light passage.

60 13. Sensing means according to claim 10,

claim 11 or claim 12, wherein the or each light sensing means is a photocell. 65

14. Sensing means according to any one of claims 1 to 9, wherein the first and second cooperating means of each sensing unit include a potentiometer comprising a resistive element with parallel extending terminals along opposite edges thereof and a contact in movable engagement with the resistive element, respectively. 70

15. Sensing means according to any one of claims 1 to 9, wherein the first and second cooperating means include a pair of adjacent photocell elements and a light source, respectively, arranged so that light from the source is directed radially onto both of the photocell elements. 75 80

16. A manipulator comprising a manipulator end effector, an end effector supporting means, and sensing means according to any one of the preceding claims, said end effector and supporting means comprising, respectively, said first and second members. 85

17. A manipulator according to claim 16, wherein said end effector comprises a pair of relatively movable members and a motor for operating the relatively movable members, the motor being mounted along the Z axis at a side of the sensing units opposite from the end effector to counterbalance the end effector. 90 95

18. A manipulator substantially as herein described with reference to Figures 1 to 7, Figures 8 to 10, or Figures 11 and 12 of the accompanying drawings.

19. A method of sensing components of force along and components of torque about mutually orthogonal X, Y and Z axes, said components being transmitted between first and second members, the method comprising: 100 105

attaching the first and second members together by resilient coupling means through which substantially the entire force and torque components are transmitted between the first and second members; 110

attaching a plurality of two-part sensing units, at locations spaced about the circumference of a circle concentric with the Z axis and in the plane of the X and Y axes, to the first and second members such that relative movement between the two parts of the sensing units is produced upon transmission of forces and torques through the resilient coupling means; 115

obtaining first electrical outputs from the sensing units in response to relative movement of the two parts along a direction parallel to the Z axis; 120

combining the first electrical outputs in respective different manners to obtain outputs respectively related to torque components about the X and Y axes and a force component transmitted along the Z axis; 125

obtaining second electrical outputs from the

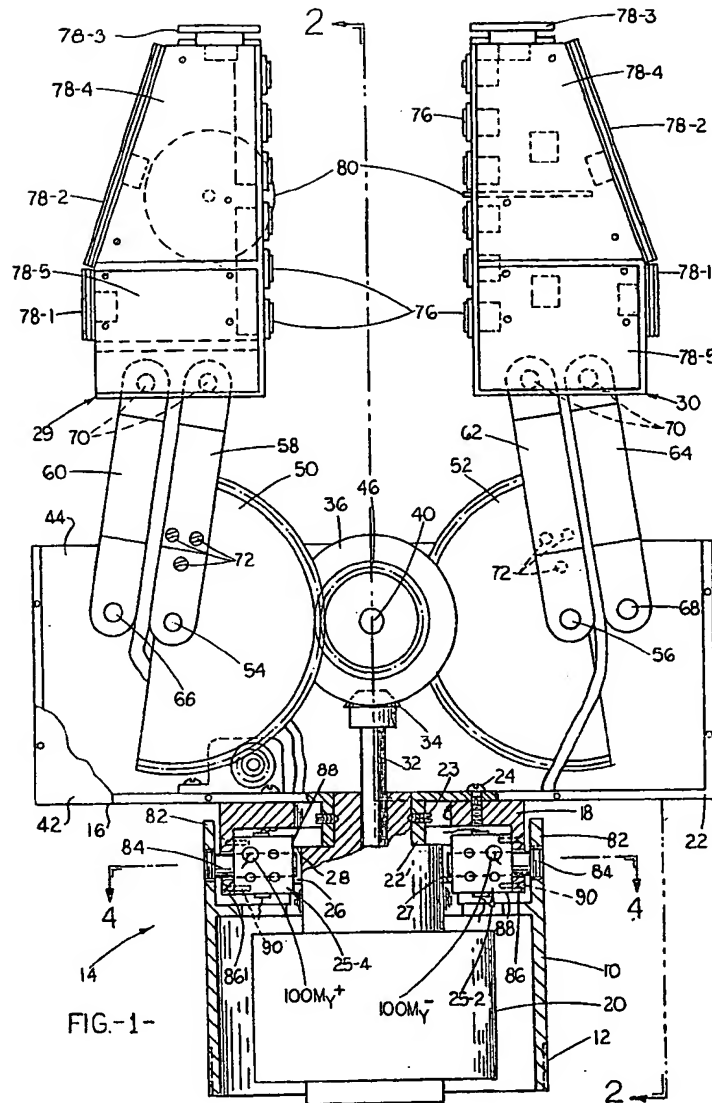
5 sensing units in response to relative movement of the two parts of each sensing unit along a direction orthogonal to a radius of the Z axis passing through the associated sensing unit and the direction parallel to the Z axis; and

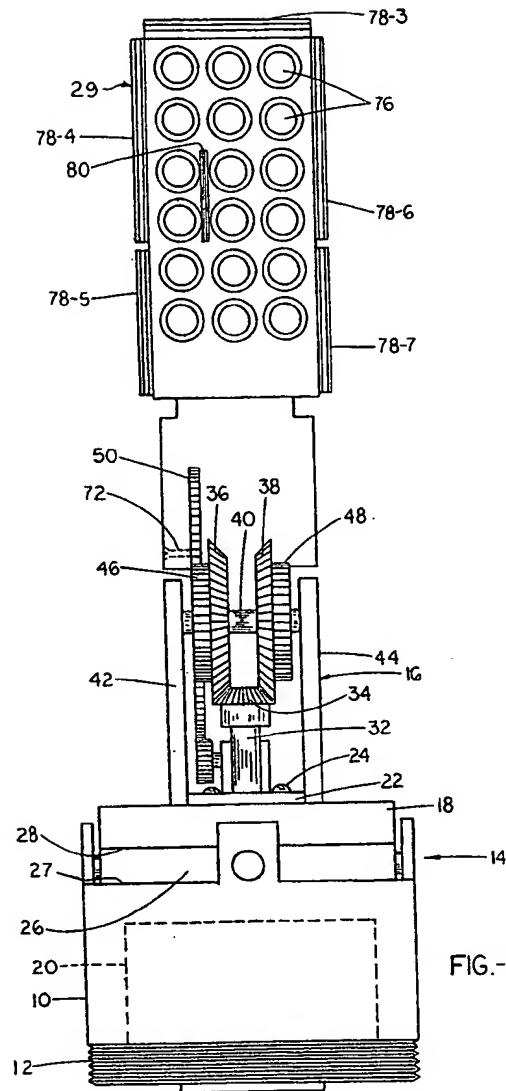
10 combining the second electrical outputs from the sensing units in respective different manners to obtain outputs respectively related to force components transmitted along the X and Y axes and a torque component about the Z axis.

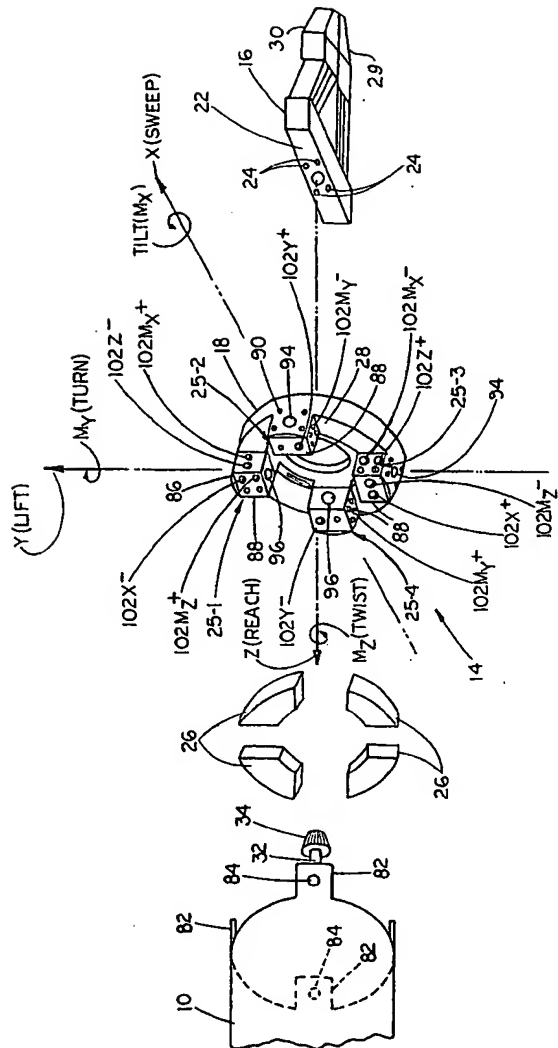
20. A method according to claim 19, substantially as herein described with reference to Figures 1 to 7, Figures 8 to 10, or Figures 11 and 12 of the accompanying drawings. 15

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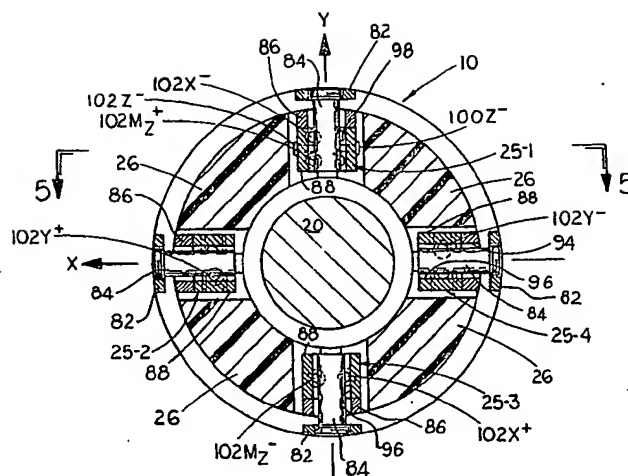


FIG.-4-

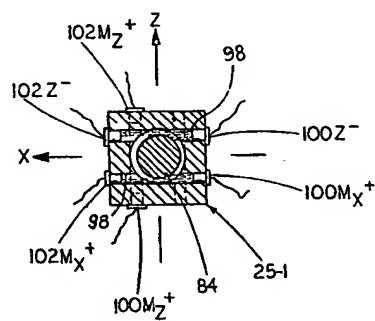


FIG.-5-

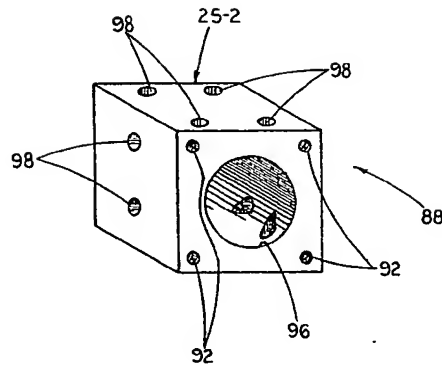


FIG. 6-

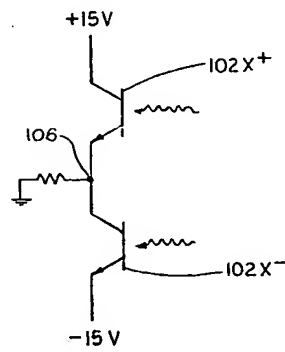


FIG. 7-

